

National Aeronautics and Space Administration



## Hybrid Electric Propulsion Technologies for Commercial Transports

### Hybrid Gas Electric Propulsion Subproject Advanced Air Transport Technology Project

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Green Aviation TIM  
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NASA LaRC

[www.nasa.gov](http://www.nasa.gov)

## Hybrid Propulsion for Commercial Transports



**Goal:** Enable the paradigm shift from gas turbines to hybrid electric and turboelectric propulsion to reduce energy consumption, emissions, and noise

### Path:

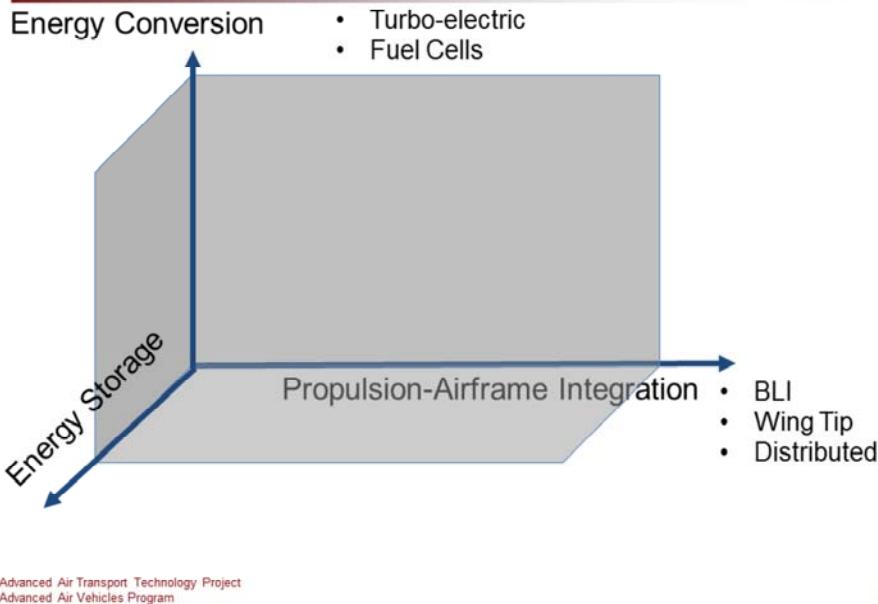
- Propulsion / Vehicle Configuration Trade Space
- Promising Propulsion / Vehicle Configurations
- Technology Challenges
- Flight Weight Technology Investment  
Combining Top-Down Analysis and Bottoms-Up Development

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2

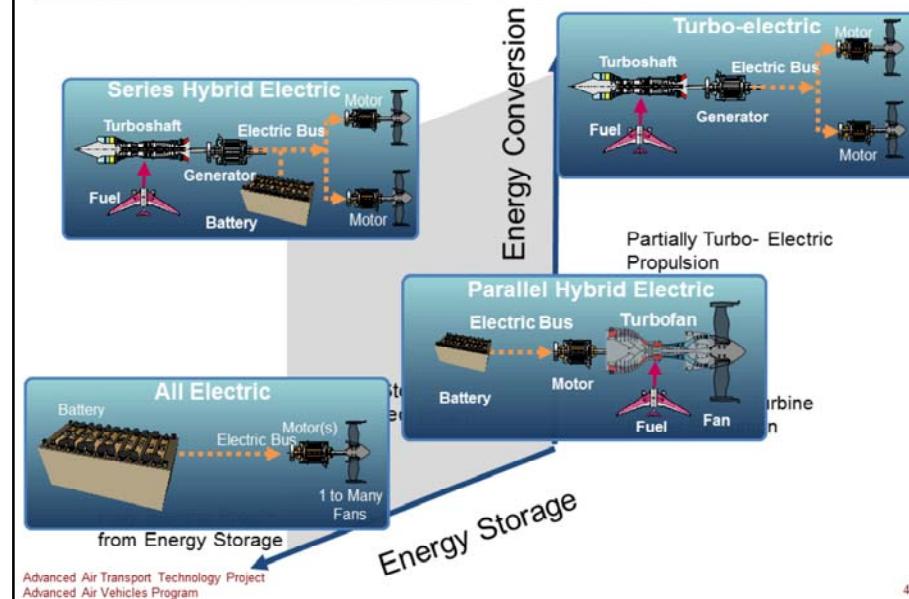
The purpose of this subproject is to expand the propulsion configurational options for transport class aircraft by the development of electric drive technologies. Today I am going to talk you through our approach to this technical challenge by reviewing how hybrid propulsion can impact aircraft design, what technologies are needed to enable hybrid propulsion, and explain how we are using the combination of top down architecture analysis and bottoms up technology development to cover this exciting area

## Hybrid Propulsion Configuration Trade Space



The key to the interest in hybrid propulsion for aviation is the way electric drive systems can influence the vehicle design trade space. For illustrative purposes, I'm going to use the notion of a 3-dimensional space with a state of the art single aisle aircraft at the origin of this cube.

## Hybrid Energy Configuration Trade Space



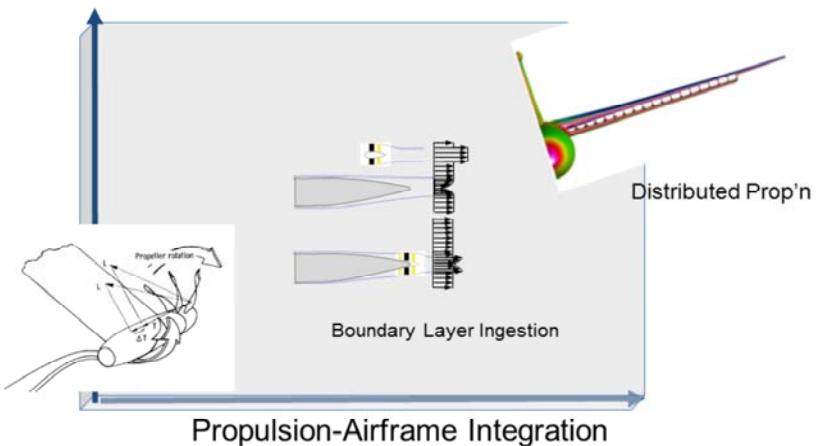
I'm showing it this way because I want you to embrace the idea that we have multiple option for changing the aircraft propulsion system. Again at our origin or baseline is all propulsive power coming from the turbine engine. There already is electricity generated at the turbine shaft, but that electricity is only used for hotel power. But just as we can adjust the bypass ratio in a traditional turbine, we can adjust how the fuel is converted in to propulsive power by going all the way to a fully turbo electric system where the turbines only produce electricity or have an intermediate state where the turbines produce both mechanical thrust and electricity for propulsion. We could envision other configurations including fuel cell energy conversion.

Along the other axis I want you to envision varying degrees of energy storage with the extreme being all propulsive power coming from entry storage charged on the ground and no energy conversion in the air. And of course between turbo and all electric we have various ways to implement hybrid electric.

## Hybrid Propulsion Configuration Trade Space



### Energy Conversion



### Propulsion-Airframe Integration

#### Wing Tip Propulsors

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5

Now, the reason we are interested in hybrid propulsion was not shown in that notional x-z plane of the trade space at all. For motivation we have to introduce propulsion airframe integration. In this notional x axis I would like you to picture bins of configurations options that improve aerodynamics. Strictly speaking, wing tip propulsors, varying degrees of boundary layer ingestion and distributed propulsion do not require hybrid propulsion. However the advancements in electric drive & distribution systems open the possibility for these PAI concepts to be implemented in new, efficient vehicle configurations.

## Hybrid Propulsion Configuration Trade Space



Energy Conversion

- Turbo-electric
- Fuel Cells

Current NRAs with RR & UTRC

- Exploring Energy Storage for turbine optimization rather than cruise

Propulsion-Airframe Integration

- BLI
- Wing Tip
- Distributed

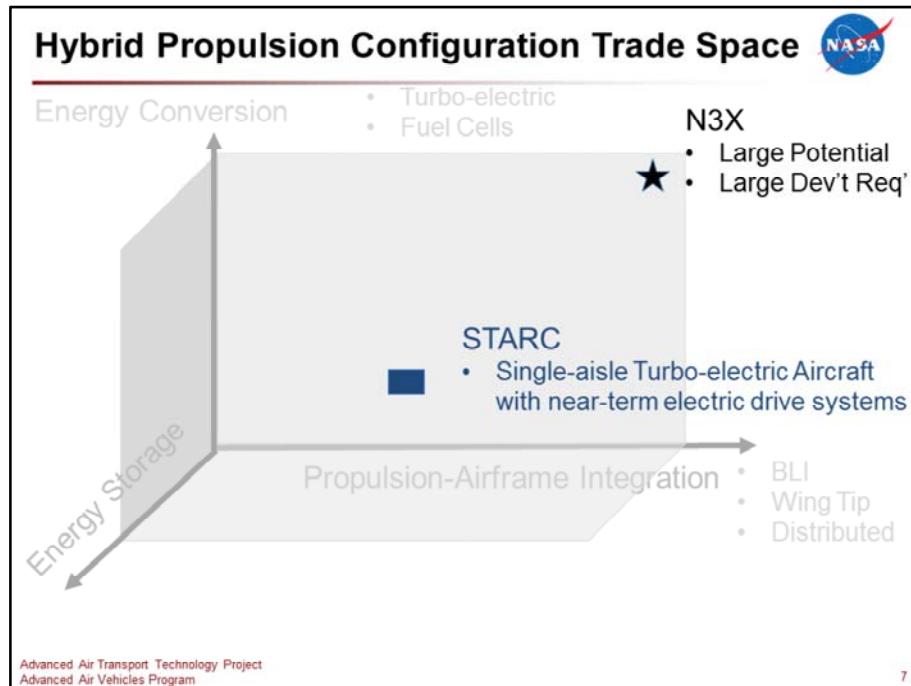
Sugar Volt

- Reduced Fuel Burn
- No Energy Reduction

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6

In this illustrative space, I am showing aircraft studies. The SUGAR Volt was a 737-like aircraft that used HEP to replace fuel with energy storage. This reduced fuel been and in flight emissions, but did not improve the overall energy efficiency of the aircraft because the configurations changes were limited. However hybridizing on wing is an attractive option for easy entry into service if an economic benefit can be identified. More advanced analysis of this sort of turbine hybridization is currently being performed under contract by UTRC & RR to see if overall mission efficiency can be gained by not only adding energy storage but by resizing other elements. Expect phase II recommendations in Oct 2016.



The N3-X was another concept vehicle but in this case it was a highly advanced, but low technology readiness, 300 passenger class craft that used hybrid wing body as well as highly efficient, fully turbo electric distributed propulsion based on superconducting technology. After exploring this advanced corner of the tradespace, NASA AATT has embarked on a series of turboelectric vehicle studies looking at potential aerodynamic-driven vehicle benefits for varying degrees of propulsion distribution.

## Preliminary Turbo Electric BLI Aircraft Design



### Single-aisle Turbo-electric AiRCraft - Aft Boundary Layer

Compared to baseline aircraft with equivalent N+3 technology

7% fuel (& energy) reduction for 900 nm mission

12% fuel (& energy) reduction for 3500 nm mission

- 2.6 MW motor (2 x 1.45 MW generators)
- Assuming 90% electric drive system efficiency
- ~45% boundary layer ingestion accounting for ~70% momentum deficit



Passengers: 154  
Range: 3500 nm  
Cruise Speed: Mach 0.7

Electric Motor	8 hp/lb	96%	3500 hp	437 lbs
Inverter	10 hp/lb	98%	3500 hp	350 lbs
Generator 2	8 hp/lb	96%	2@1937 hp	484 lbs
Cable 2 x 93' @ 750 V / 1926 amps	3.85 kg/m	99.6%	1.44 MW	482 lbs
Circuit Protection	0.5 * Cable Wt			240 lbs
Thermal Management System (ROM)	0.68 kW(th)/kg	279	kW(th)	906 lbs
Total Electrical + TMS				2921 lbs

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Welstead et al., Presented at AIAA Sci Tech Jan. 2016

8

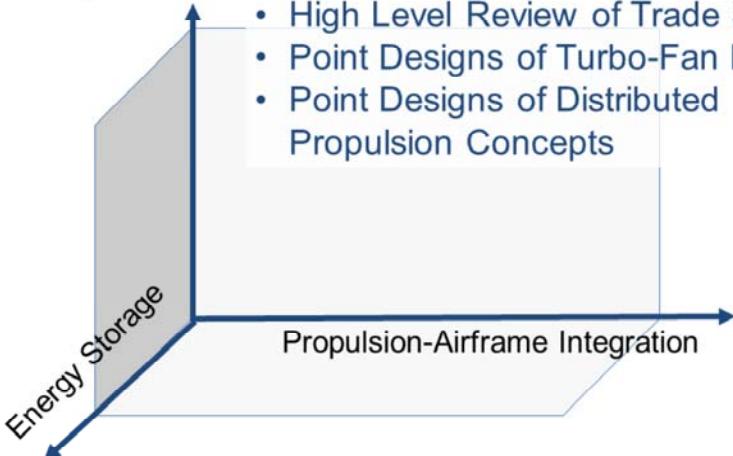
Recent effort has been applied to assessing the feasibility of a minimal turbo electric distributed propulsion application at 150 PAX. This studied resulted in a nominal 10% fuel burn reduction compared to a N+3 baseline, with modest technology advancement assumptions. It is important to note that this a preliminary study, but it is an important preliminary study because it suggests at least one configuration with notable energy improvements with technology assumption that appear to be feasible in the 10-20 year time frame

## Hybrid Propulsion Configuration Investment



### Energy Conversion

- High Level Review of Trade Space
- Point Designs of Turbo-Fan Hybrids
- Point Designs of Distributed Propulsion Concepts



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9

To recap let me summarize NASA's investment in large aircraft hybrid propulsion. We have a cooperative agreement with academia to develop a top level understanding of the hybrid prop trade space for a range of vehicle sizes. Again, we have ongoing contacts with industry to do carefully analysis of hybridization of turbine engines in order to learn if any propulsion efficiency can be obtained without changing the vehicle design. And we are investing in point design analysis of some specific distributed propulsion vehicle concepts to understand the benefits & penalties of these configurations.

## Hybrid Propulsion Technical Development



For closure with net energy benefit, need subsystem improvements

	All Electric	All Turbo-electric	Hybrid Turbo Fan	Partial Turbo-electric
Electric Drive System	high	high	high	high
Turbine Power Extraction	low	high	med.	high
Thermal Management Systems	high	high	high	high
Energy Storage	high	low	high	med.

Starting with Electric Drive System technology as foundational and highest risk.

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10

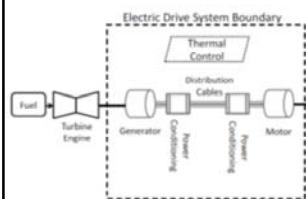
Now I'm switching gears from top down analysis to bottoms up tech development. The subsystems supporting hybrid propulsion can be binned in a number of ways. Here I'm showing bins of e drive, etc. For a number of reasons that I won't go into now, we have chosen to focus first on the electrical drive system

## Electric Drive Technology for Aircraft

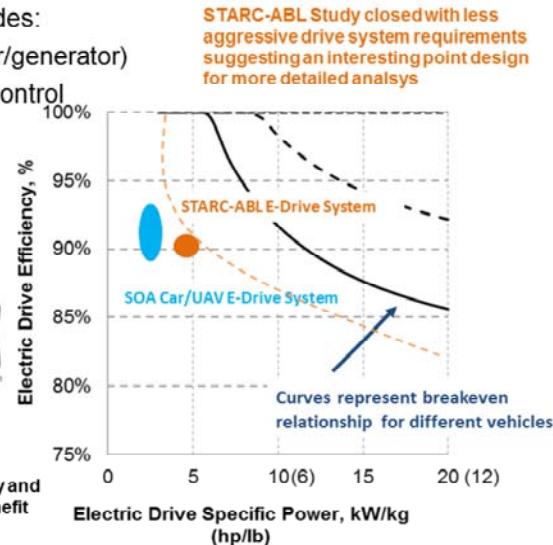


### Electric Drive System Includes:

- Electric Machines (motor/generator)
- Power Management & Control
- Power Architecture
- Power Distribution
- Thermal Management



Breguet range equation analysis suggests the balance of efficiency and specific power needed for net benefit (upper right corner)



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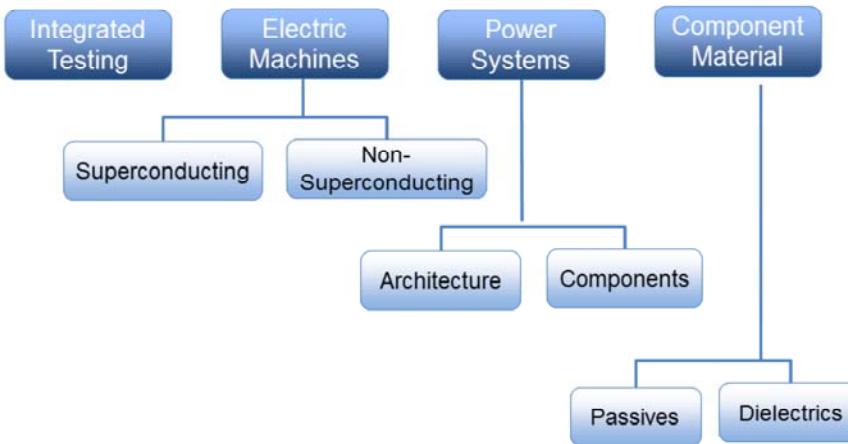
Jansen et al., Presented at Prop & Energy 2015 (AIAA 2015-3890)

11

When I say e drive, I am including  
Electric machines  
Power management and control  
Power architecture  
Power distribution

Electric machines were identified as a true long pole components since existing high power machines are far from the specific powers required for flight systems. To understand the relationship of key performance parameters of electric drive systems for turbo electric aircraft, Breguet range equation analysis was used to bound electric drive system weight versus fuel burn benefits using generic assumptions of aerodynamic benefit. Here the black solid and dotted lines represent a break even line with points above the line providing net benefit. It is interesting to note that the single motor driven fan configuration appears to have a lower break even line than the nominal ones calculated for a more highly distributed system.

## Electric Drive Technology Development



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12

Our strategy for investing in bottoms up technology development includes both farther term investment in fundamental materials and superconducting technology as well as investment in nearer term exploration of advanced machine topologies, power systems and integrated testing of electric drive subsystems

## Integrated System Testing



- Confirm Component Development
- Validate Power System benefit predictions
- Develop Flight Control Methodology for Distributed Propulsion
- Study component interactions to validate performance & matching at steady-state and transient operation



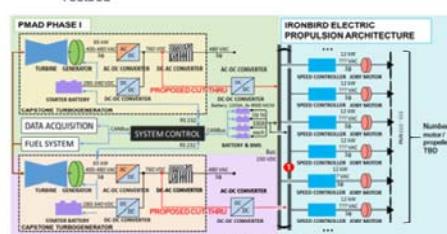
NASA-GRC PEGS  
Software/Hardware emulation  
hardware-in-the-loop electrical grid



NASA-AFRC HEIST  
200kW Ironbird → Flight  
Simulation Hardware in the  
Loop



NASA-AFRC Flight simulator – Flight  
Dynamics



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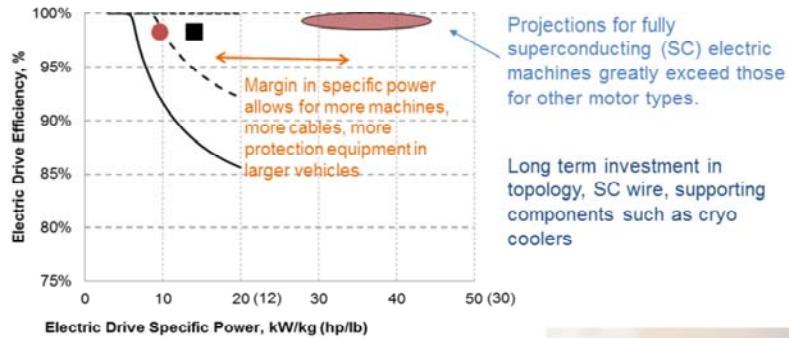
13

## Enabling System Testing

## Superconducting Electric Machines



Superconducting (infinitely small direct conduction loss) leads to much higher specific power and greatly enhances feasibility for larger aircraft dist. propulsion



Projections for fully superconducting (SC) electric machines greatly exceed those for other motor types.

Long term investment in topology, SC wire, supporting components such as cryo coolers



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14

## Non-Superconducting Electric Machines



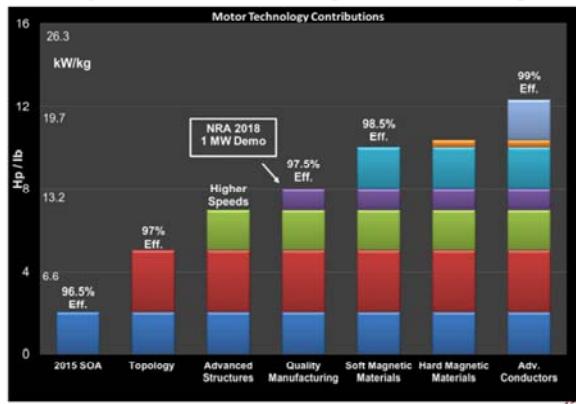
Rapid advancements in machines and power electronics makes flight weight electrical drives in the realm of feasibility

Improved motor/generator topology options enabled by advanced power electronics

Better specific power or power density due to aeronautic design & manufacturing processes.

Emerging wide-band gap semiconductors and advance soft magnetic materials enable high frequency operation with lower switching-frequency losses

New materials and fabrication developments will push specific power farther



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15

## Flight Weight Power



Rapid advancements in machines and power electronics makes flight weight electrical drives in the realm of feasibility

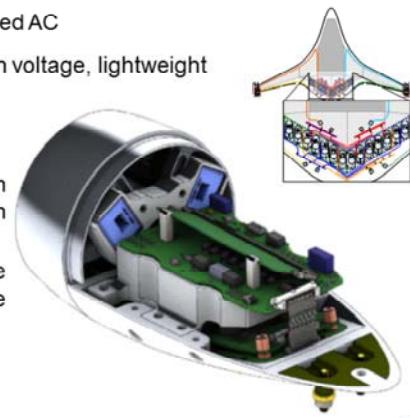
**Architecture:** Contracts with Rolls-Royce and GE to analyze and develop modeling tools for Superconducting Turbo Electric Power Architectures (N3-X like)

**Grid Topology:** High Voltage DC, Doubly-Fed AC

**Components:** Building prototype 1MW, high voltage, lightweight power inverters"

**Devices & Protection equipment:**

- Advanced component topologies can allow lower power devices to be used in high power applications
- Underlying material advancements are greatly reducing the weight and volume of power conversion devices



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16

## Hybrid Propulsion Summary



### Why:

- Hybrid propulsion systems for aircraft can enable expand configuration options

### What:

- Combine Top-Down Analysis with Bottom-Up Technology Development to identify at least one transport class configuration that can yield overall energy reduction

### How:

- Industry, Academia and NASA investment in
  - System Analysis
  - Integrated System Testing & Analysis
  - Electric Machines & Power Components
  - Enabling Material Development

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17



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18

## NASA NRA – 1MW Motor Development



### NASA Sponsored Motor Research

- 1MW
- Specific Power > 8HP/lb (13.2kW/kg)
- Efficiency > 96%
- Awards
  - University of Illinois
  - Ohio State University
- Phase 1 work completed
- Phase 3 to be completed in 2018

### NASA Sponsored Inverter Research

- 1MW, 3 Phase AC output
- 1000V or greater input DC BUS
- Ambient Temperature Awards
  - 3 Years (Phase 1, 2, 3)
  - GE – Silicon Carbide
  - Univ. of Illinois – Gallium Nitride
- Cryogenic Temperature Award
  - 4 years (Phase 1, 2, 3)
  - Boeing – Silicon CoolMOS, SiGe

#### Ambient Inverter Requirements

Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch Target	25	15.2	99.5

#### Cryogenic Inverter Requirements

Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	17	10.4	99.1
Goal	26	15.8	99.3
Stretch Target	35	21.3	99.4

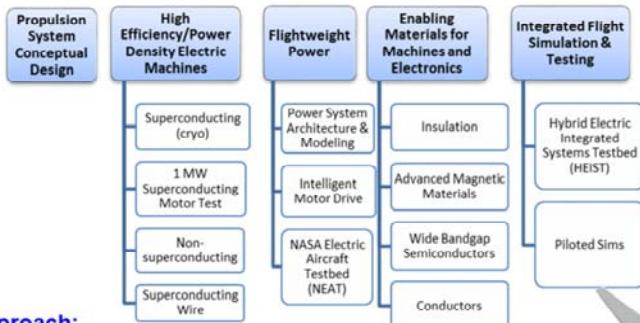
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19

## Hybrid Gas Electric Propulsion SubProject (HGEP)



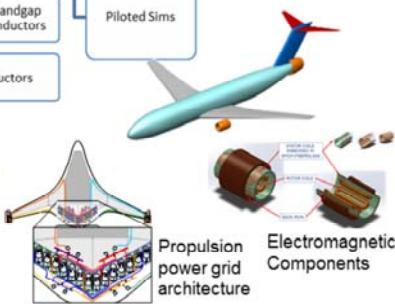
### Technical Areas:



### Approach:

- Detailed assessment of *reference design concept* through modeling and analysis
- 200 kW Subscale System Demo's on *hardware-in-the-loop* and flight simulation testbed
- Select Architecture and Component Demo's at *1-2 MW Level*
- Component maturation for key enabling materials and subcomponents

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20

Non traditional propulsion architecture .....

Long term is 3-4X, in the next 5 year, 2X at TRL3

Achieve **3-4X increase in the specific power** of high efficiency electric components and alternate power conversion systems, and 3-4X increase in stored energy density for storage devices to make 10 mega-watt onboard power generation and/or utilization feasible for propulsion

### Key Challenges for Next 5 Years:

- Low ac-loss superconducting stator
- High conductivity coil , integration of motor design, structural concepts, and thermal management, for non-cryogenic, high power density motor

### High Level Technical Challenge for 5 years:

- 2X increase in power density of electrical motor

### How is it done today ? What are the limits of current practice ?

- **SOA superconducting** motors with **power density 6hp/lb** with use of superconducting rotor and Cu stator, non-superconducting stator limits power density
- Power density for **SOA ambient temperature motor is 3 hp/lb**, experimental small motor have 5 hp/lb power density; limited by conductivity of Cu, temperature limits of constituent materials, thermal management and structural integrity
- SOA cryocoolers have 30 lb/hp power density, limited by heavy heat exchanger

### What is new in our approach ?

- Superconducting electric motor with superconducting rotor and low ac-loss stator
- Adv. non-cryogenic motor with high conductivity coil (e.g., Cu-CNT composite, CNT), improved thermal management concepts, and new structural concepts.
- High power density cryocooler with advanced lightweight recuperator design

## Example of Specific Power Improvements



Drive	Motor Type	Baseline Materials		Improved Materials	
		Specific Power kW/kg (HP/lb)	Eff.	Specific Power kW/kg (HP/lb)	Eff.
Stand.	SPM	10.6 (6.4)	95.1%	14.5 (8.8)	97.4%
	IPM	10.4 (6.3)	96.6%	14.0 (8.5)	98.3%
	SRM	4.6 (2.8)	93.5%	4.9 (3.0)	97.1%
	IM	3.5 (2.1)	94.8%	4.9 (3.0)	97.6%
Tip Drive	SPM	9.6 (5.8)	90.9%	12.0 (7.3)	93.3%
	IPM	9.8 (6.0)	96.5%	12.0 (7.3)	97.7%
	SRM	8.7 (5.3)	96.4%	9.6 (5.8)	98.3%

This table shows examples of how material advancements can impact various electric machine specific power and efficiencies. In these cases, the motors WERE NOT re-optimized for the new materials, so more improvements are possible.

Surface-Mounted PM Motor (SPM)    Interior PM Motor (IPM)    Interior PM Tip Motor (IPM)    Synchronous Reluctance Tip Motor (SRM)    Synchronous Reluctance Motor (SRM)    Induction Motor (IM)

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21

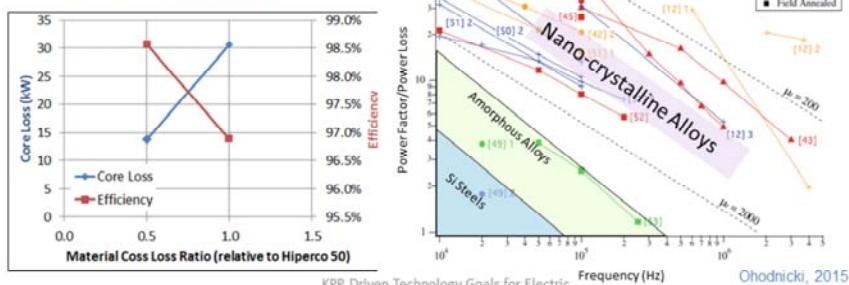
## Electric Machine Development Potential



Motor analysis was used to study the performance sensitivity to new materials

Developmental magnetic materials have been shown to increase efficiency in electric machines and power electronics

- Machine (or electronic) efficiency goes up with switching frequency but magnetic losses go up with switching frequency
- Amorphous and nano-crystalline magnetic materials have demonstrated lower power loss losses



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KPP Driven Technology Goals for Electric  
Machines and Power Systems

Ohodnicki, 2015

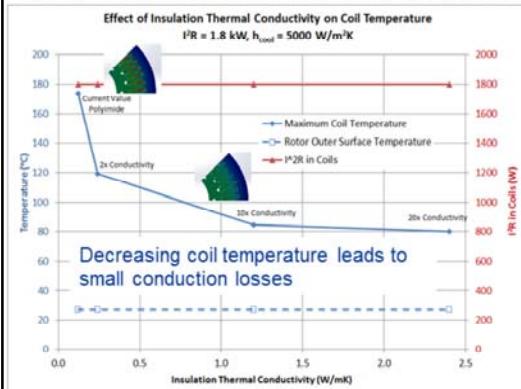
22

- Soft magnetic materials are a critical element in power generation, conditioning, and conversion technologies.
- Improvements in the efficiency of these materials is essential for achieving the performance levels that are required to enable hybrid electric systems.
- Soft magnetic materials enable low loss inductive switching, which is useful in inductor, transformer and filter applications.
- Laminated electrical steels traditionally used for power cores become inefficient at high switching frequencies.
- Nanocrystalline soft magnetic alloys have the greatest potential for achieving these energy efficiencies.

## Electric Machine Development Potential



Motor analysis was used to study the performance sensitivity to new materials



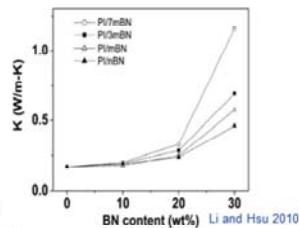
- Can Increase Conductivity by
  - Polymer chemistry
  - nano-composites

BN has the potential to impact both thermal conduction and electrical resistance

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- Increasing wire insulation thermal conductivity allows faster heat removal for lower conduction losses.

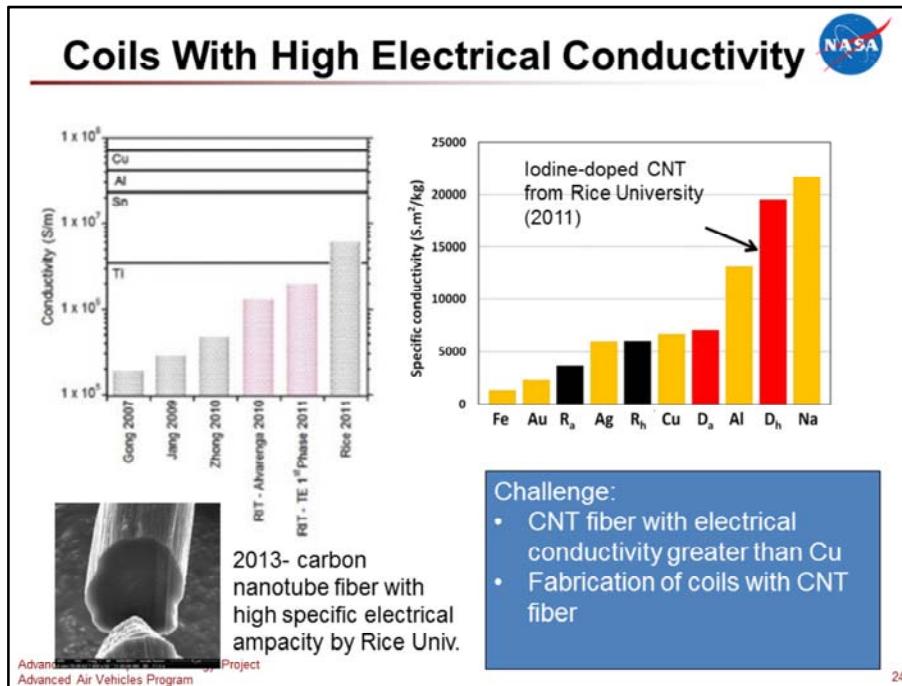
- Increasing dielectric breakdown voltage allows thinner insulation for tighter coil coupling with volume & electromagnetic benefits



23

Increasing the thermal conductivity of electrical insulators in order to reduce electrical losses due to temperature-induced increases in resistivity

Decreasing diameter of winding wires by increasing dielectric breakdown of insulators (allowing thinner insulating coatings)



Wang Adv Fnc Mat 24(21) 2014

The current-carrying capacity (CCC), or ampacity, of highly-conductive, light, and strong carbon nanotube (CNT) fibers is characterized by measuring their failure current density (FCD) and continuous current rating (CCR) values. It is shown, both experimentally and theoretically, that the CCC of these fibers is determined by the balance between current-induced Joule heating and heat exchange with the surroundings. The measured FCD values of the fibers range from  $10^7$  to  $10^9$  A m<sup>-2</sup> and are generally higher than the previously reported values for aligned buckypapers, carbon fibers, and CNT fibers. To the authors' knowledge, this is the first time the CCR for a CNT fiber has been reported. The specific CCC value (i.e., normalized by the linear mass density) of these CNT fibers are demonstrated to be higher than those of copper



## Low AC loss MgB<sub>2</sub> conductor development

### Successful strand design recipe:

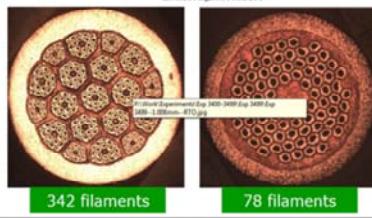
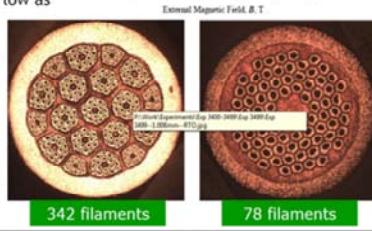
- small  $d_{eff}$
- small twist pitch
- resistive matrix
- non-magnetic sheaths
- higher  $T_{op}$  (e.g. 20K); lower  $B_{op}$  (e.g. 0.6T)

$J_c$  measured with 10  $\mu\text{m}$  filaments at 0.29 mm. Work progressing to get obtain 10  $\mu\text{m}$  filaments with larger wire diameters.

$J_c$  maintained with twist pitches as low as 10 mm.



Hyper Tech



From Tomsic, et al, 2015 ASC Presentation, "Development of MgB<sub>2</sub> superconductor wire and coils for practical applications" Cryogenic Engineering Conference (Tucson, June 28-July 2, 2015)

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KPP Driven Technology Goals for  
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25